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**REGULAR ARTICLE**

# Automated Programming of Micro- and Single Electron Nanosystems

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The article examines the features of the automated design of micro- and single electron nanosystems focused on the implementation of programmable logic functions. In this work, structured programming does not mean the development of algorithms for processing multi-argument functions by changing working programs, as reproduced by a microcontroller, but rather technological changes in configurations and settings of large micro- and nanosystems in such a way as to implement functions at the logical-structural level. The main advantage of circuit programming over specialized ones is lower cost, which is important in small-scale production. The use of multiplexers in micro- and nanocircuits makes it possible to implement a variety of Boolean and majority functions necessary for the construction of logic elements. The proposed methods provide the ability to effectively configure logic circuits, including multi-functional blocks for implementing complex logic operations. The paper presents the results of the implementation of the latest technologies for automated programming of single-electron nanocircuits with quantum cellular automata. Using a modern automated design system (computer-aided design) QCA Designe, majority and Boolean functions based on nanomultiplexers were synthesized. Simulation of timing diagrams under cryogenic temperatures confirmed the loss of their operability in space conditions. The results of computer design of single electron nanodevices obtained in the article confirmed their advantages over microelectronic analogues in terms of minimal energy consumption and higher speed. The presented results and their analysis indicate opportunities for further improvement of micro- and nanoelectronics design technologies.

**Keywords**: Programmable logical structures, Micro- and single electron nanocircuits, Majoritary functions, Automated programming, Multiplexers, Criogenic tempretures.

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## 1. INTRODUCTION

Automated design of micro- and single electron nanosystems with programmable logic does not involve the possibility of creating algorithms for processing multi-argument input functions by changing working programs, as is usually implemented in microcontrollers. This refers to the introduction of technological changes to the internal structure of electronic circuits to ensure the synthesis of the necessary functions at the structural and logical level.

## 2. ANALYSIS OF THE LATEST RESEARCH

The development of research in the field of programmable micro- and nanocircuits is gaining momentum, and significant attention of researchers is directed to the automated hierarchical design of such systems. The first significant achievements in this field became possible due to the creation of multi-structural systems based on universal functionally complete modules, which are a promising trend in the development of modern electronics [1]. These works demonstrate the possibilities of automated design of micro- and nanocircuits capable of implementing 16 two-argument and 256 three-argument functions using multiplexers [2]. However, there are serious difficulties in optimizing these circuits, which causes their considerable complexity and limits the universality of application. An important aspect of research has become the improvement of micro- and single electron nanocircuits programming methods for the implementation of various functions of logical algebra [3]. Scientists proposed effective algorithms for automated programming of microcircuits with a high level of integration, which became the basis for the further development of single electron nanodevices with programmable structures [4]. Despite significant progress in this area, the issue of achieving effective automated design is still relevant, and the problem of simplifying algorithms and their exact reproduction is the subject of active discussions [5].

The effect of temperature conditions on the performance of single electron nanocircuits requires special attention, in particular, operation at cryogenic temperatures [6]. Studies indicate that such conditions can significantly affect the operation of nanodevices, which stimulates the search for new approaches to increase their quality and stability of functioning [7]. Also, the problem of synchronizing these schemes remains relevant, which creates additional challenges for their implementation. Thus, the issues of improving the quality of micro- and nanocircuits with programmable logic remain important and require further research and improvement [8].

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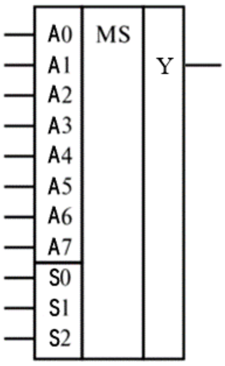
## 3. DESIGNING COMBINATIONAL MICROCIRCUITS ON MULTIPLEXERS

To use multiplexers in the design of combinational micro- and nanocircuits, the signals of some arguments of the reproduced function are fed to the address inputs, and the information inputs play the role of programmable nanostructures.

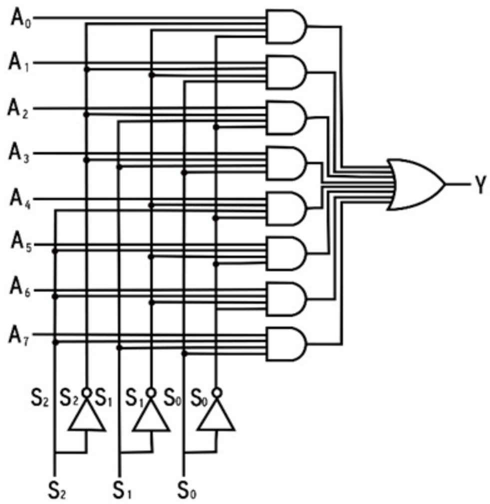
Fig. 1 shows the conventional designation (a) of the multiplexer (8→1).




a)

| S2 | S1 | S0 | Y |
|---|---|---|---|
| 0 | 0 | 0 | A0 |
| 0 | 0 | 1 | A1 |
| 0 | 1 | 0 | A2 |
| 0 | 1 | 1 | A3 |
| 1 | 0 | 0 | A4 |
| 1 | 0 | 1 | A5 |
| 1 | 1 | 0 | A6 |
| 1 | 1 | 1 | A7 |

b




c

**Fig. 1** – Multiplexer (8→1) (a), its truth table (b) and its equivalent microcircuit (c)

From the truth table after the transformations, the function of the logic algebra of the multiplexer (8→1) takes the form:

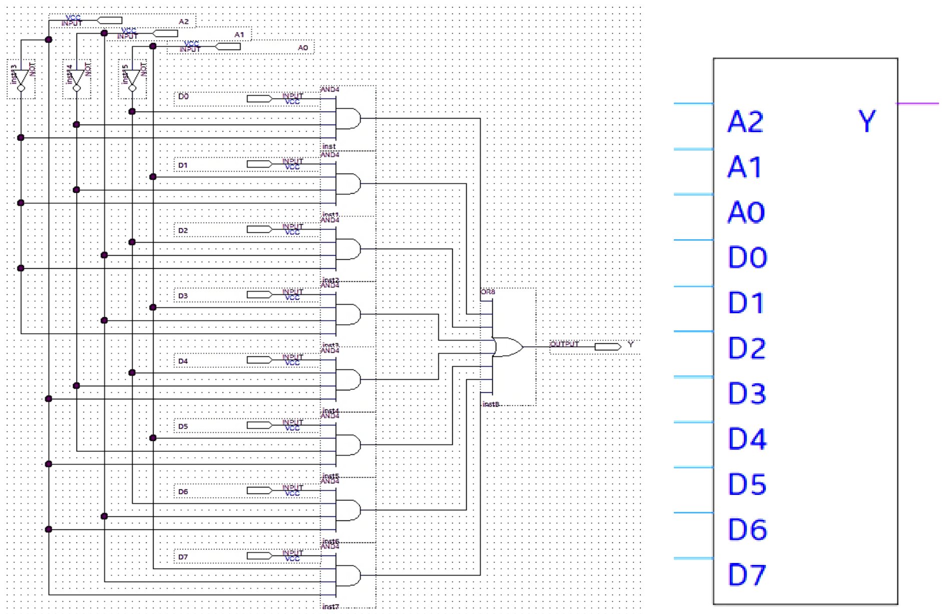
$$Y = \overline{S0}\,\overline{S1}\,\overline{S2}A0 + \overline{S0}\,\overline{S1}S2\,A1 + \overline{S0}S1\overline{S2}A2 + \overline{S0}S1\,S2\,A3 + S0\overline{S1}\,\overline{S2}A4 + S0\overline{S1}S2\,A5 + S0\,S1\overline{S2}A6 + S0\,S1\,S2\,A7 \quad (1)$$

To reproduce four-argument functions, it is necessary to carry out a transformation to obtain disjunctive normal forms (DNF). Using, for example, de Karnaugh map for the function:

| **X1X2\X3X4** | **00** | **01** | **11** | **10** |
|---|---|---|---|---|
| **00** | 0 | 1 | 0 | 1 |
| **01** | 0 | 0 | 0 | 1 |
| **11** | 1 | 1 | 0 | 1 |
| **10** | 0 | 1 | 1 | 1 |

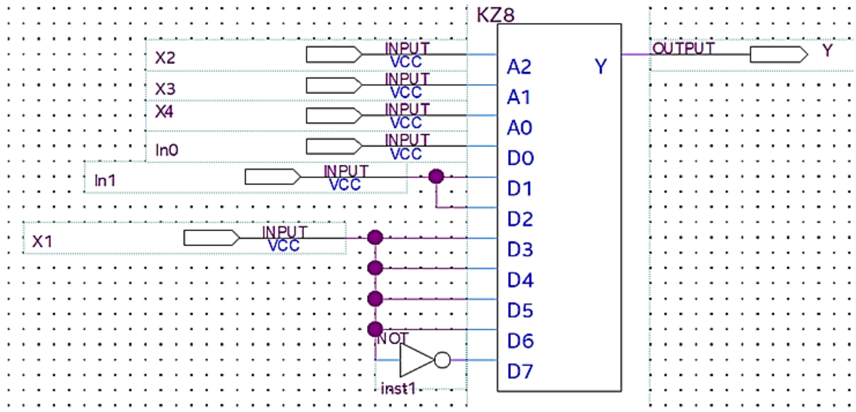
we will get its minimized DNF:

$$y = x3\overline{x4} + \overline{x2}\,\overline{x3}x4 + x1x2\overline{x3} + x1\overline{x2}x3 \quad (2)$$

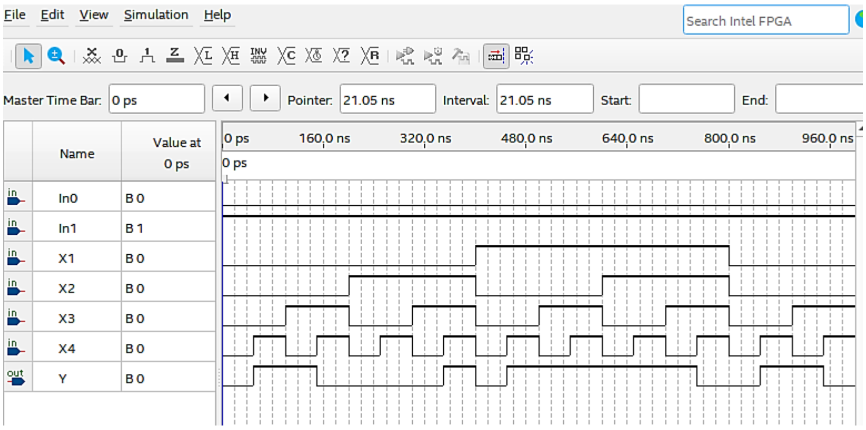



a b

**Fig. 2** – Eight-input PMNM on microelements (a) and in the macrobody (b)




a




b

**Fig. 3** – Automated configuration of PMNM (a) and time diagram of the programmed function (b)

## 4. RESULTS AND THEIR DISCUSSION

The final programming table of the eight-input programmable micronanomultiplexer (PMNM) (8→1) for the implementation of four-argument functions was obtained from the above examples (Table I). According to fig. 1c, the PMNM was built on the basis of the computer-aided design system (CAD) Quartus [7] (Fig. 2) from logical elements (a) and from a separate element in one case in the form of a macro diagram (b).

In Fig. 3 shows the scheme of the computer implementation of function (2) on the PMNM (a), which is configured in the disjunctive canonical form of the conjunctions of the constituents of the unit according to the truth Table 1:

$$f = \sum(1,2,7,9,10,11,12,13,14) \qquad (3)$$

Let's decompose the previously obtained function by the older variable, as a result of which it will have the form:

$$f = \overline{x1} * [+(1,2,7)] + x1 * [+(1,2,3,4,5,6)] \qquad (4)$$

From equation (4) we obtaine the next algoritm programming of the multiplexer (8→1):

1) apply $\overline{x_1}$ to input 7;
2) apply $x_1$ to inputs 3,4,5,6;
3) apply 1 to inputs 1,2;
4) apply 0 to input 0.

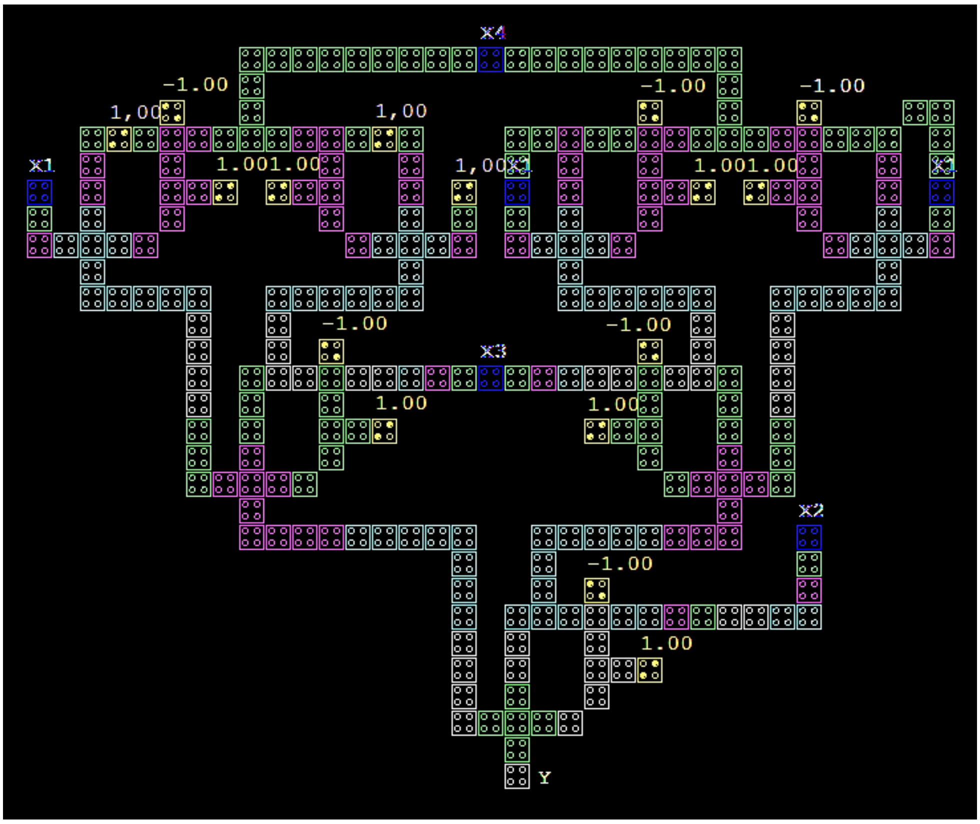
Figure 3b shows the simulation results of function (4).

**Table 1** – Summary truth table for the function (4)

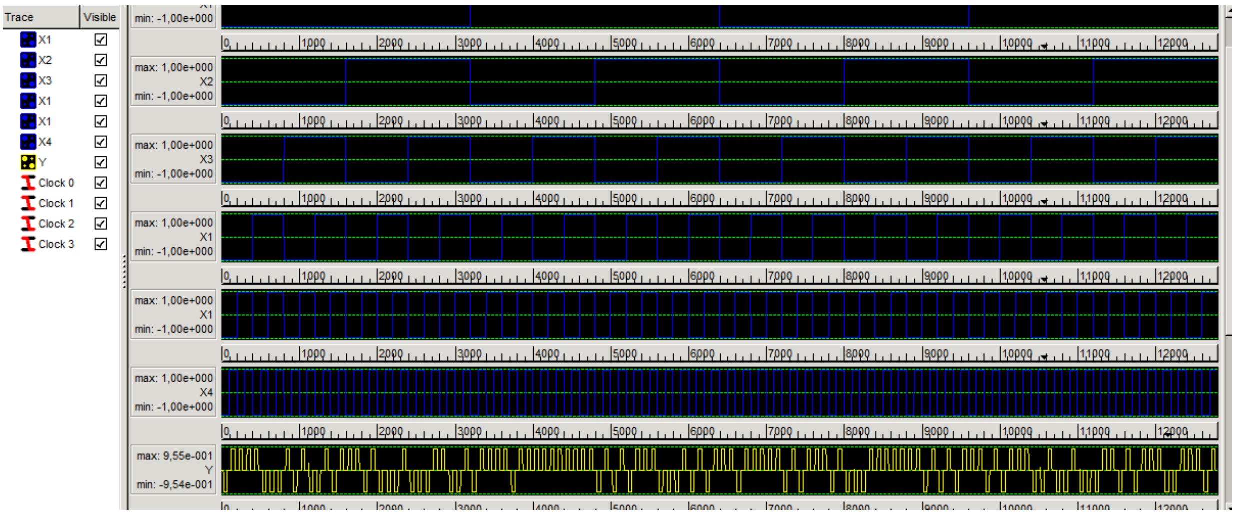
| X1 | X2 | X3 | X4 | Y |
|---|---|---|---|---|
| 0 | 0 | 0 | 0 | 0 |
| 0 | 0 | 0 | 1 | 1 |
| 0 | 0 | 1 | 0 | 1 |
| 0 | 0 | 1 | 1 | 0 |
| 0 | 1 | 0 | 0 | 0 |
| 0 | 1 | 0 | 1 | 0 |
| 0 | 1 | 1 | 0 | 0 |
| 0 | 1 | 1 | 1 | 1 |
| 1 | 0 | 0 | 0 | 0 |
| 1 | 0 | 0 | 1 | 1 |
| 1 | 0 | 1 | 0 | 1 |
| 1 | 0 | 1 | 1 | 1 |
| 1 | 1 | 0 | 0 | 1 |
| 1 | 1 | 0 | 1 | 1 |
| 1 | 1 | 1 | 0 | 1 |
| 1 | 1 | 1 | 1 | 0 |

Quantum cellular automata (QCA) is a paradigm of computing, according to which information is represented by a certain configuration of electrons in the cell of the QCA, which is formed from one or two separate molecules [8]. Devices based on this technology consist of nanoscale dielectric cells with four quantum semiconductor dots located at the corners and two mobile electrons [9].

The previously created PMNM is now implemented on the basis of single-electron majority nanocircuits on CAD QCADesigner [6] (Fig. 4a). It is designed on the basis of schemes from Fig. 2a and Fig. 3a and consists of 24 majority elements (ME) that perform the functions of logical elements. Fig. 4b illustrates the results of modeling its time diagrams, which completely coincide with the truth table (Fig. 1c).



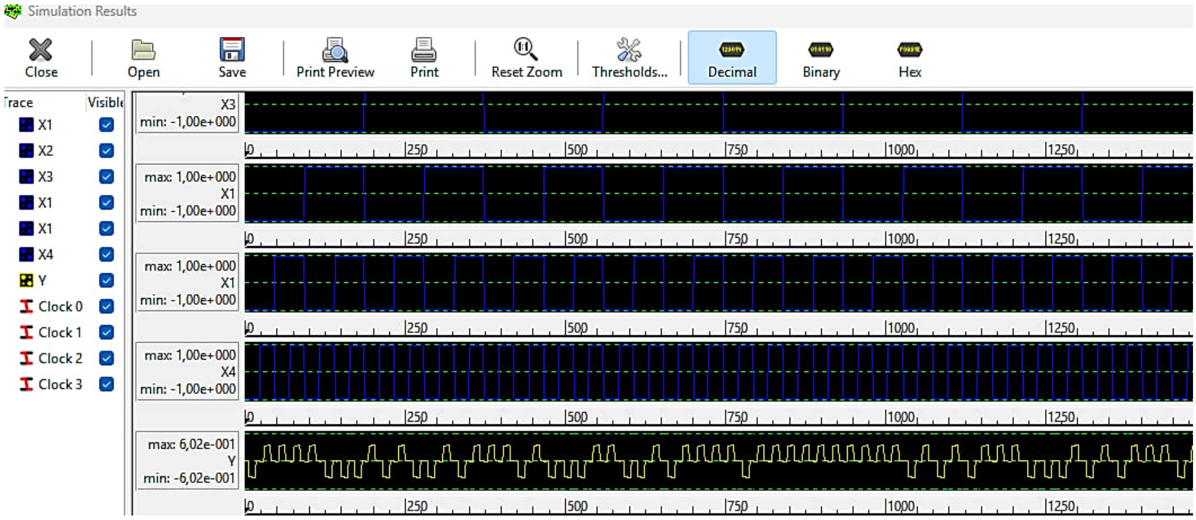

a



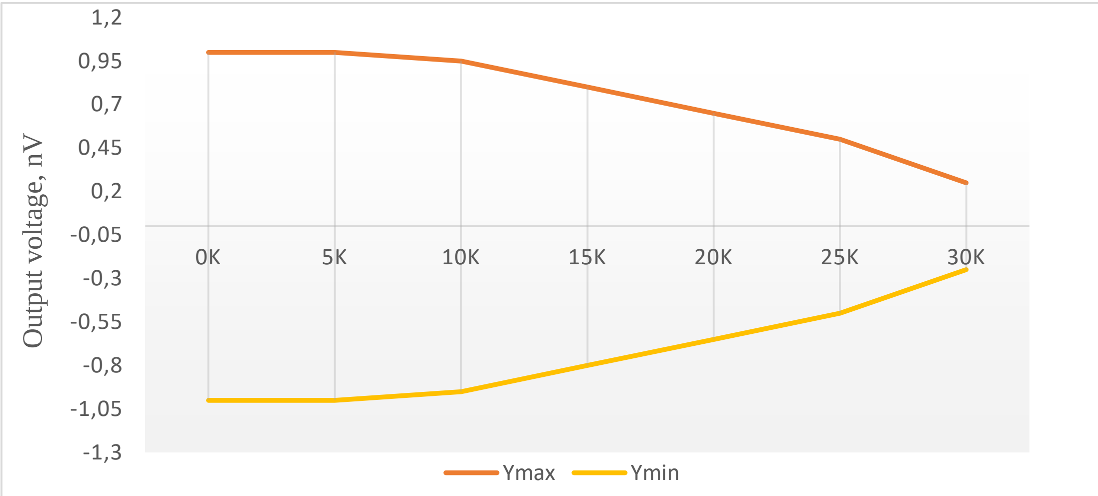

b

**Fig. 4** – Programming PMNM on quantum cellular automata (a) and oscillograms of operation (b)

Figure 5 shows the generalized results of simulation of the effect of cryogenic temperatures on the functioning of PMNM. Obviously, with even an insignificant increase in temperature from 0 to 25 K, not to mention up to 300 K, the ability of PMNM to perform logical operations is completely lost (Fig. 5a). MEs become unable to detect single, informationally important, electrons under conditions of increasing concentration of thermally generated background charge carriers (Fig. 5b). This, in turn, makes it impossible for single-electron nanocircuits on spacecraft to fail even at cryogenic and, especially, at normal temperatures [10].




a




b

**Fig. 5** – Rezults of modeling for decline pulse characteristics of PMNM at cryogenic temperatures: a) degradation of initial characteristics at $T = 20$ K, b) its graph of temperature dependence

## 5. CONCLUSIONS

As a result of the executed research, methods of automated programming of micro- and nanosystems based on multiplexer structures were developed, which demonstrate high efficiency in the reproduction of complex logical functions. The created algorithms allow flexible configuration of programmable structures for the implementation of both Boolean and majority functions, which significantly expands the functionality of single-electron nanocircuits. Modeling confirmed the adequacy of the developed micronanomultiplexers, and also revealed their advantages in frequency characteristics. However, the low-temperature regime remains critical for their stable operation, which requires further research to optimize thermal performance. Thus, the article contributes to the development of automated design technologies, offering effective solutions for creating reliable and flexible nanosystems. Thus, single-electron nanocircuits based on the component base of quantum automata retain their functionality only under the conditions of operation on board space vehicles.

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## Автоматизоване програмування мікро- та одноелектронних наносистем

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У статті досліджено особливості автоматизованого проектування мікро- та одноелектронних наносистем, орієнтованих на реалізацію програмованих логічних функцій. У цій роботі під структурним програмуванням розуміється не розробка алгоритмів обробки багатоаргументних функцій шляхом зміни робочих програм, відтворених мікроконтролером, а технологічні зміни конфігурацій і налаштувань великих мікро- і наносистем таким чином, щоб реалізовувати функції на логіко-структурному рівні. Головна перевага схемного програмування перед спеціалізованим – менша вартість, що важливо при дрібносерійному виробництві. Застосування мультиплексорів у мікро- та наносхемах дозволяє реалізувати різноманітні булеві та мажоритарні функції, необхідні для побудови логічних елементів. Запропоновані методи забезпечують можливість ефективного конфігурування логічних схем, у тому числі багатофункціональних блоків для реалізації складних логічних операцій. У роботі наведено результати впровадження новітніх технологій автоматизованого програмування одноелектронних наносхем з квантовими комірковими автоматами. За допомогою сучасної системи автоматизованого проектування (комп'ютерного проектування) QCA Designe синтезовано мажоритарні та булеві функції на основі наномультиплексорів. Моделювання часових діаграм в умовах кріогенних температур підтвердило втрату їх працездатності в космічних умовах. Отримані в статті результати комп'ютерного проектування нанопристроїв підтвердили їх переваги перед мікроелектронними аналогами щодо мінімального енергоспоживання та більшої швидкодії. Представлені результати та їх аналіз вказують на можливості подальшого вдосконалення технологій проектування мікро- та одноелектроніки.

**Ключові слова:** Програмовані логічні структури, Мікро- та одноелектронні наносхеми, Основні функції, Автоматизоване програмування, Мультиплексори, Кріогенні температури.